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doi:10.15199/48.2016.06.27

Electro-thermal numerical model of superconducting tape

***Abstract**. The paper presents assumptions and construction of a numerical simulation model of a part of second-generation superconducting tape. It presents a scheme of developed model in the Scilab / Xcos environment with Coselica toolbox. The simulation results are also presented for superconducting tape under condition of subcritical, supercritical current, and for short-term fault current.*

Streszczenie.** Artykuł prezentuje założenia i budowę numerycznego modelu fragmentu taśmy nadprzewodnikowej II generacji. Zaprezentowano schemat modelu opracowany w środowisku Scilab/Xcos z toolbox'em Coselica, wraz z wynikami eksperymentu symulacyjnego obejmującego analizę zachowania taśmy przy prądzie podkrytycznym, nadkrytycznym oraz przy krótkotrwałym prądzie zwarcie. **Elektro-termiczny model numeryczny taśmy nadprzewodnikowej

Keywords: Superconductivity, numerical simulation.
Słowa kluczowe: Nadprzewodnictwo, symulacje komputerowe.

Introduction

Computer simulations are important tools to modeling and analysis of electrical devices and phenomena. One of the methods of computer modeling is to build string models in programs such as Labview, Matlab/Simulink, Scilab/Xcos or Modelica. Such models are built using specialized computing units performing specific tasks.

Building models for numerical simulation of superconducting phenomena and devices is a complex issue. It ensues from the non-linear nature of the superconductor materials. Resistivity and critical parameters are dependent on each other, as shown in Fig. 1.

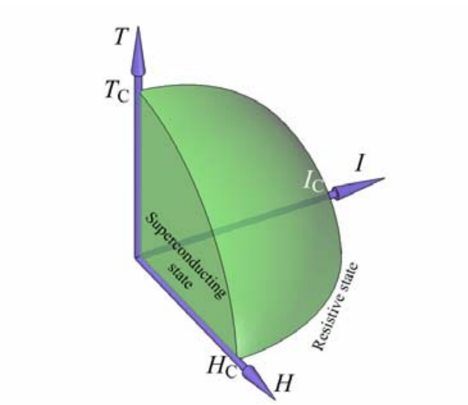

Fig.1. Superconducting state with critical parameters of superconducting material

In the case of string models, the development environment should enable the construction of coupled models (eg. thermo-electric) and allow to design and build new arithmetic blocks. Scilab/Xcos with Coselica Toolbox. is the optimal calculation program that ensures compliance with all established requirements.

This paper presents the numerical model of superconducting tape and description of authorial calculation blocks used in built computer model of superconducting tape.

Superconducting tape

The main application of superconducting materials are tapes, used to build complex superconducting devices, like fault current limiters, transformers, separators or SMES. There are two types of superconducting tapes, first and second generation, as shown In Fig.2. Currently the second type superconducting tapes, called thin film tapes, are more popular. They are formed by sputtering of each layer on the substrate construction.

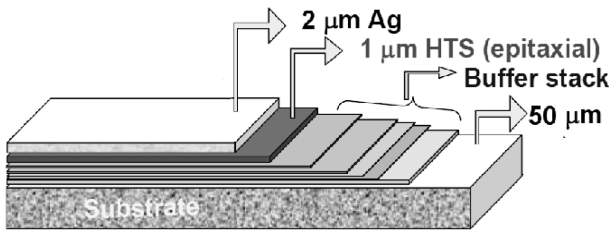

Fig.2. The structure of the second generation thin film HTS tape [1]

Electrical parameter of superconducting tape, like resistivity, strongly depends on the three parameters: current density in superconductor, external magnetic flux density and temperature of the superconductor [3]. Exceeding the critical value coresponding to each of listed parameters, causes a sharp increase in the value of superconductor resistance. This may result in overheating of the tape and consequently can lead to its burnout.

An important issue is therefore to analyze and study the spread of the resistive zone in the superconductor.

Liquid nitrogen cooling

One of the basic problems in building thermo-electric coupled models of superconducting devices is complex description of heat exchange between superconductor and liquid nitrogen.

LN cooling efficiency does not depend directly on the nitrogen temperature, but on the temperature difference between the cooled object and the coolant. This process has been studied experimentally and is described as the characteristics shown in Fig. 5 [1].

As can be seen from the characteristics, after reaching a peak, nitrogen bath cooling efficiency decreases rapidly. This property can make emergency situations related to the sharp increase current more than the critical value, involve an increased risk of physical damage of the superconductor. This ensues from rapid decrease in nitrogen bath cooling efficiency related to increase of temperature difference between superconductor and LN.

Mathematical model in Coselica

Coselica is a free implementation of the Openmodelica for Scilab/Xcos environment. It provides tools to support mathematical, modeling of electrical circuits, thermal issues and mechanical problems. It gives possibility to create coupled thermo-electric models.

An important feature of Coselica is open source code that allows modification and adding new blocks.

For the purposes of model, author has developed two new blocks.

First one is responsible for the simulation of superconducting element, as shown in Fig. 2. Numerical model of the calculating block takes into account two critical parameters of the superconductor operating state.

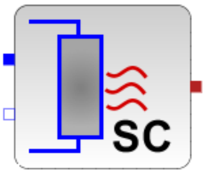

Fig.3. Calculaling block of the superconductor

The mathematical model implemented in the block is based on the equations describing the dependence of the superconductor resistance on temperature and current [2]:

$$R_n = R_r + \frac{R_{n\_\max}}{e^{I_c(T)-|i_n(t)|}+1} \quad (1)$$

$$I_C(T) = I_{C_0}\left(\frac{T_C - T}{T_C - T_0}\right) \quad (2)$$

where: R_n – superconductors resistance, R_r – residual resistance of a superconductor, R_{n_max} – superconductor resistance at resistive state, I_c – critical current, i_n – temporary value of superconductor current, T – superconductor temperature, T_c – critical temperature, I_{c0} – critical value of current at the reference temperature, T_0 – reference temperature

The block has three ports, regarding input current, output current and heat port.

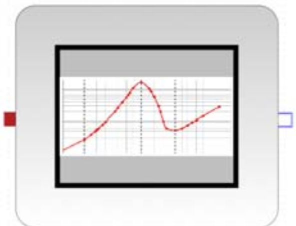

Fig.4. Simulations block of the heat exchange on the border of the HTS tape and the liquid nitrogen

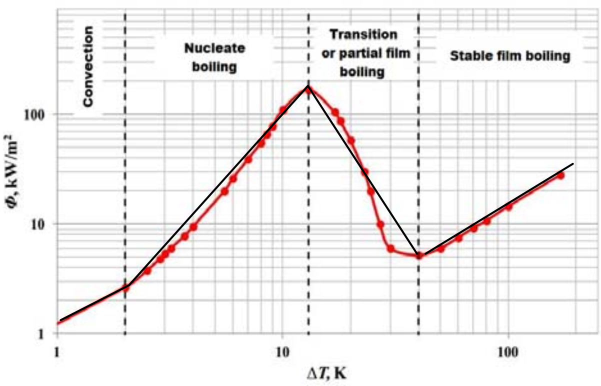

Fig.5. Measurement characteristics boiling curve and its linear approximation for cryogenic liquids

The second developed block is responsible for simulation of the heat exchange between the metallic material and the liquid nitrogen, as shown in Fig. 5.

Mathematical model of block was based on approximation polygon curve characteristics approximation, as shown in Figure 3. The developed model curve is approximated by four sections, as shown in Fig. 5.

The adopted model approximation describes well the actual exchange model. Only in the third temperature range the polynomial approximation would give more accurate results.

Block analyzing the temperature difference between the heat ports and selecting a suitable range determines the possible heat flux.

Superconducting tape model

The numerical model of superconducting tape was developed for simulation of the circuit shown in Fig. 6.

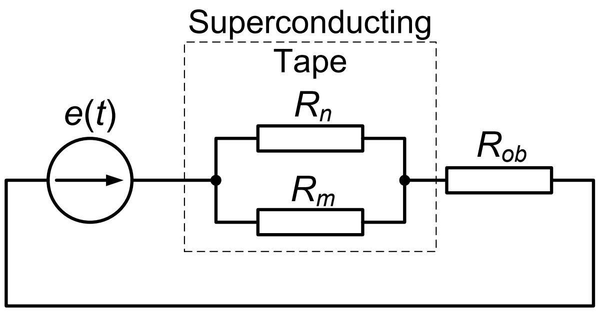

Fig.6. Simplified diagram of the simulated circuit

In the construction of the numerical model, some simplifying assumption were made, limiting the number of layers of tape up to two metallic and superconducting R_m and R_n, wherein only the metal layer is in contact with liquid nitrogen.

The analyzed portion of the tape is divided into ten parts, thereby releasing ten coupled with each other sections of the model. The proposed superconducting tape model takes into account nonlinearity of the superconducting material, current distribution between section of parallel-to-serial connected superconductor-resistor. Melts and heat exchange between the tape and the cooling medium (liquid nitrogen).

According to the assumptions the coupled thermo-electric model was developed with separate ten sections of superconducting tape, as shown in Fig 7.

The model has also two additional sections. First one controls the load resistance, in order to simulate an fault current, and the second one is for temperature measurement of the individual sections of the superconducting tape.

Simulation results

The operation analysis for proposed model was made in three cases:

a) at high load impedance and the subcritical current $i<I_C$, as shown in Fig.8 and Fig.9

b) for small values of the load impedance and high current values $i> I_C$, as shown in Fig.10 and Fig.11

c) for step change in load impedance causes the appearance of the fault circuit current $i_a> I_C$, as shown in Fig.12 and Fig.13

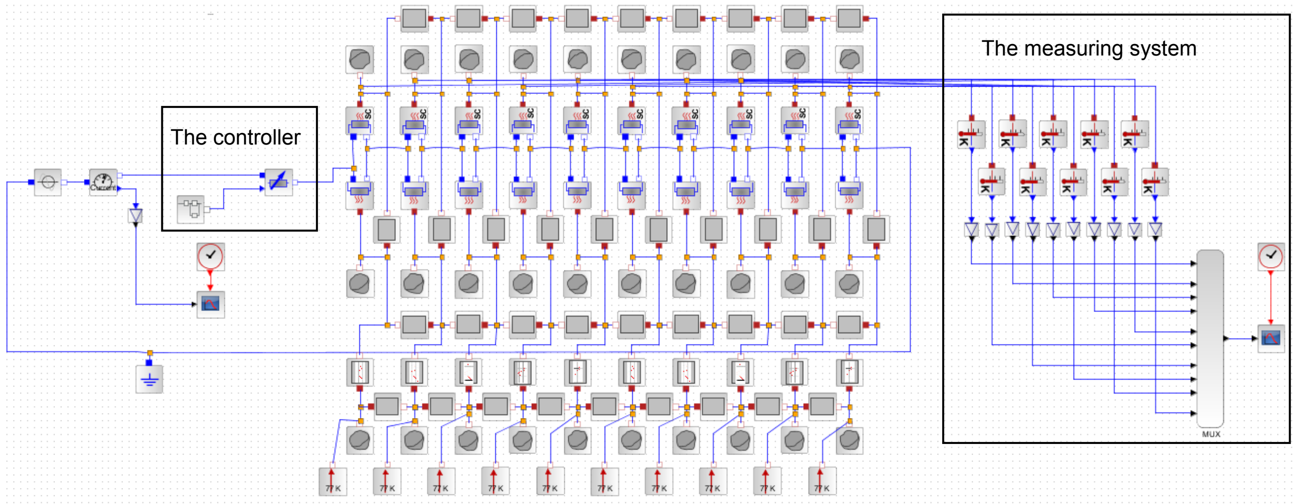

Fig.7. Diagram of superconducting tape simulation model

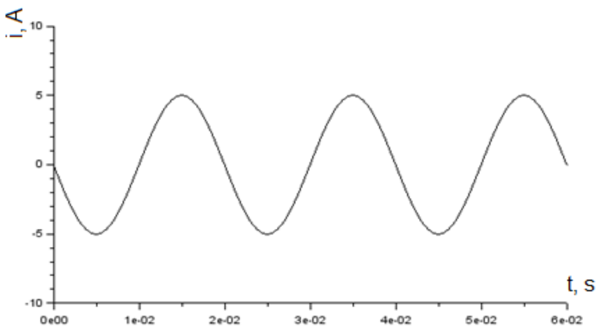

Fig.8. The current waveform in the circuit for the case a

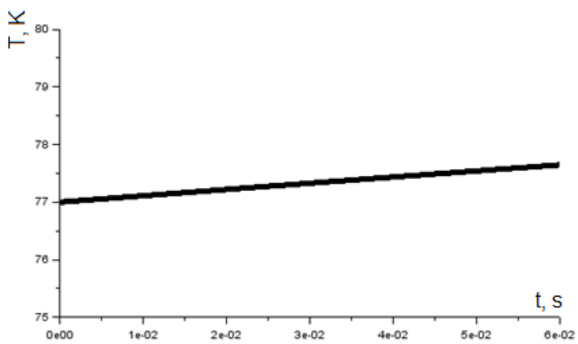

Fig.9. Temperatury a superconductor for the case a

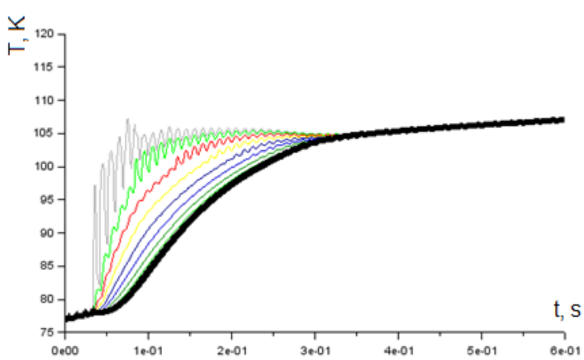

Fig.10. The current waveform in the circuit for the case b

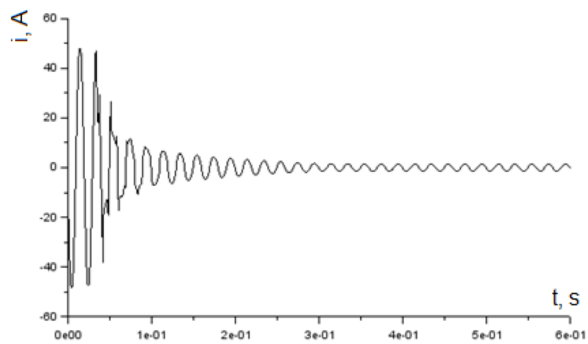

Fig.11. Temperatury of superconductor at individual sections for the case b

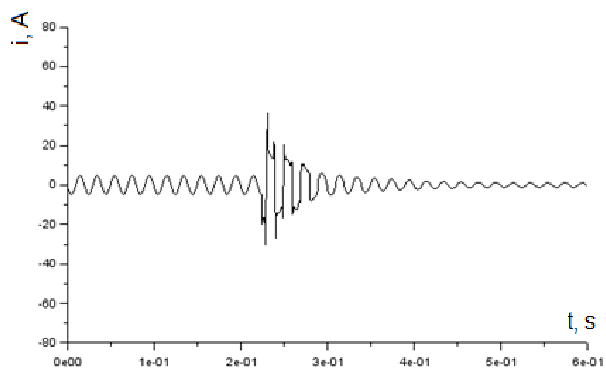

Fig.12. The current waveform in the circuit for the case c

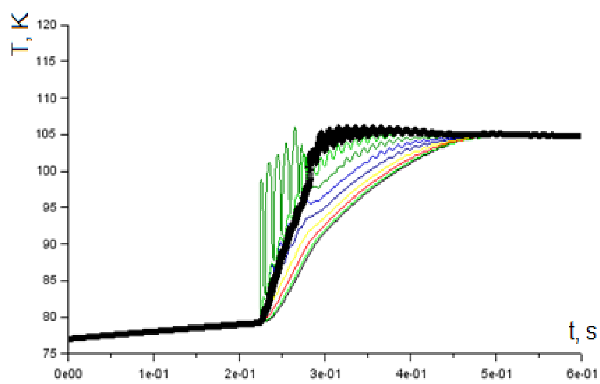

Fig.13. Temperatury of superconductor individual sections for the case c

It can be noticed gradual loss of superconductivity by individual sections of tape, which is confirmed by experimental studies [4]. In opposition to the measurements, in the simulation each segment comes one after the other, in fact, a resistive zone may appear in any section of the tape. This may be the result of material and structural features and the occurrence of some local imperfections in the construction of a portion of the tape.

Conclusion

In spite of some imperfections numerical model of superconducting tape, well illustrates the phenomena occurring in the analyzed portion of the tape. It seems that further fine-tuning should be responsible for part of the heat transfer in liquid nitrogen and the introduction in this part of the model discretization calculations.

Mathematical model will also be modified, due to the limited impact of the heat exchange between the individual layers of tape.

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